Channel Estimation in Tag Collision Scenarios

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***Abstract*—Multiple tags in Radio Frequency Identification (RFID) systems are scheduled by a medium access control layer using the Framed Slotted Aloha (FSA) or binary tree protocol. The focus of our research is on FSA and passive Ultra High Frequency (UHF) RFID. In current standards, only one tag can be acknowledged per slot. In this work we propose the increase of the theoretical throughput of FSA RFID systems with multiple antennas for physical layer collision recovery by acknowledging two tags per slot. The expected throughput increase is approximately 5.03 times the throughput of a conventional reader. In order to profit of such increase we propose a method for channel estimation with a modified tag response, a so-called "postpreamble". The influence of the channel estimation on the performance is investigated through simulations.**

I. Introduction

Radio Frequency Identification (RFID) is a wireless identification technology that usually operates in a multiple RFID tag environment. On the Medium Access Control (MAC) layer all tags, within the coverage area of the reader, are scheduled using the Framed Slotted Aloha (FSA) or binary tree protocol. In this work our focus is on FSA as defined in the second-generation EPCglobal standard for passive Ultra High Frequency (UHF) RFID [1]. Since only slots with a single tag response can be decoded successfully, in FSA the maximum identification rate is achieved when the number of tags matches the number of slots in a frame [2].

In spite of this, different groups investigated slots with signals originating from colliding RFID tags: Khasgiwale et al. [3] developed techniques to extract information from communication collisions involving passive UHF RFID tags. They used information from the tag collisions on the physical layer to estimated the number of colliding tags. With this additional information they increased the accuracy of tag population estimate. Moreover, they showed that it is possible to recover from collisions and correctly read the data of the colliding tags. Knerr et al. in [4] developed the maximum likelihood estimator for the tag population in FSA protocols. Their method can be used to update the frame size, during the frame duration, based on the probability level of the current slot-by-slot estimate. In [5], Holzer et al. presented an improvement of the FSA. Their algorithm is suitable for the applications where the tag population size is known in advance. The authors are examining the first half of the frame and if they find an event with low probability they restart the frame. Yu et al. [6] propose an anti-collision algorithm based on smart antenna technology. The authors divided the reader field into sectors and used FSA or binary tree search in each sector. They have not tried to recover from collisions. Shen et al. [7] presented a practical design of an RFID reader that is capable of reading multiple passive tags through joint decoding. They focused on low frequency tags and analyzed the signal constellations of the colliding tags. Furthermore, they simulated the error performance when multiple colliding tags were present and they proposed an algorithm for collision recovery. Mindikoglu et al. [8] showed how to separate multiple overlapping tag signals using an antenna array in combination with blind source separation techniques. In contrast to their work, Angerer et al. [9], proposed receivers which require a channel estimate. They achieved an increase of the theoretical throughput for the FSA RFID systems with physical layer collision recovery receivers. The authors observed that the proposed channel estimation and single antenna receivers are only capable of recovering from collisions of two tags and that multiple antenna receivers can recover from a collision of a number of tags that is less or equal than the number of receiving antennas when the channel is known at the receiver. Furthermore, Kaitovic et al. [10] presented an extension to more receiving antennas at the reader side which can separate up to R tags, transmitting in the same slot, as long as the number of colliding tags is not larger than the collision recovery factor $M = 2N_{\mathrm{RA}}$, where N_{RA} is the number of receiving antennas on the reader.

In this work we propose a channel estimation technique and analyze by simulation the influence of the channel estimation on the performances. Additionally, we investigate the throughput increase of an FSA protocol with receivers that are capable of recovering from collisions $(R \leq M)$ and acknowledging two tags $(J = 2)$ in one slot.

The rest of paper is organized as follows: The received signal model and receiver structure are described in the following Section II. The theoretical increase in performance of an FSA system with the capability of recovering from collision on the physical layer and acknowledging two tags is discussed in Section III. In Section IV the proposed channel estimation method is explained. The analysis of the performance is conducted in Section V. The last section finally concludes the paper.

II. Multi Antenna RFID Reader

We envision an RFID reader with a single transmit antenna and N_{RA} receive antennas.

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A. Received Signal

The signal received at the antennas is first downconverted to the baseband. When R tags are responding simultaneously, the complex-valued baseband signal at the receive antenna i is

$$s_{c,i}(t) = \sum_{j=1}^{R} h_{i,j} a_j(t) + I_i(t) + n_i(t), \qquad i = 1,..,N_{\mathrm{RA}} \quad (1)$$

where $s_{c,i}(t)$, $I_i(t)$, $n_i(t)$ are the complex values of the received signal, the carrier leakage and noise at the i^{th} antenna, respectively. Furthermore, $a_j(t)$ denotes the modulation signal of tag j, and $h_{i,j}$ denotes the channel coefficient between reader, the j^{th} tag and the i^{th} receive antenna, as shown in Fig. 1. Each channel coefficient $h_{i,j}$ is modeled as the multiplication of a forward channel ${h_j}^f$ and a backward channel ${h_{i,j}}^b$ as explained in [10].

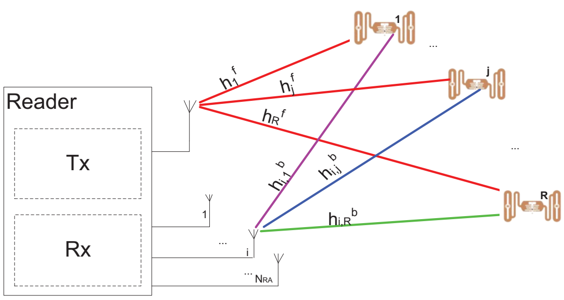

Fig. 1. Channel model with N_{RA} receiving antennas and R tags.

Sticking the received signals of each antenna into a vector, we can rewrite Equation (1):

$$\mathbf{s_c}(t) = \mathbf{H_c}\mathbf{a}(t) + \mathbf{I}(t) + \mathbf{n}(t). \quad (2)$$

Here, $\mathbf{H_c}$ represents the $N_{\mathrm{RA}} \times R$ channel matrix and $\mathbf{a}(t)$ is the $R \times 1$ modulation vector. The terms $\mathbf{s_c}(t)$, $\mathbf{I}(t)$, $\mathbf{n}(t)$ are the $N_{\mathrm{RA}} \times 1$ column vectors with the elements $s_{c,i}(t)$, $I_i(t)$ and $n_i(t)$, respectively.

Considering the fact that $a_j(t)$ is real-valued [10], the received signal described by Equation (2), can be equivalently reformulated to:

$$\begin{bmatrix} \Re\{\mathbf{s_c}(t)\} \\ \Im\{\mathbf{s_c}(t)\} \end{bmatrix} = \begin{bmatrix} \Re\{\mathbf{H_c}\} \\ \Im\{\mathbf{H_c}\} \end{bmatrix} \mathbf{a}(t) + \begin{bmatrix} \Re\{\mathbf{I(t)}\} \\ \Im\{\mathbf{I(t)}\} \end{bmatrix} + \begin{bmatrix} \Re\{\mathbf{n}(t)\} \\ \Im\{\mathbf{n}(t)\} \end{bmatrix}, \quad (3)$$

where $\Re\{\cdot\}$ selects the real part and $\Im\{\cdot\}$ selects the imaginary part of the argument. As a result the number of equations is doubled, therefore the separation of up to $R_{\max} = M = 2N_{\mathrm{RA}}$ tags is feasible.

The carrier leakage is assumed to be perfectly canceled to simplify the following equations. Moreover, the channel matrix and the received signals have the form:
$\mathbf{H} = \left[\Re\{\mathbf{H_c}\} \;\; \Im\{\mathbf{H_c}\}\right]^T$, $\mathbf{s}(t) = \left[\Re\{\mathbf{s_c}(t)\} \;\; \Im\{\mathbf{s_c}(t)\}\right]^T$.

B. Minimum Mean Square Error Receiver - MMSE

An MMSE receiver is proposed in [10] in order to separate signal components using multiple receive antennas. The MMSE receiver offers a balance between noise enhancement and ISI mitigation [11]. The signal at the output of the MMSE receiver is:

$$\mathbf{r}_{\mathrm{MMSE}}(t) = \left(\hat{\mathbf{H}}^H\hat{\mathbf{H}} + \sigma^2\mathbf{I}_R\right)^{-1} \hat{\mathbf{H}}^H \cdot \left(\mathbf{s}(t) - \hat{\mathbf{H}}\bar{\mathbf{a}}(t)\right), \quad (4)$$

where $\hat{\mathbf{H}}$ is the matrix of the estimated channel and $\hat{\mathbf{H}}^H$ denotes its Hermitian transpose. Additionally, $\bar{\mathbf{a}}(t) = E\{\mathbf{a}(t)\}$, σ^2 is the noise power, and $\mathbf{I}_R$ denotes the $R \times R$ identity matrix.

III. FSA with Collision Recovery

According to the EPCglobal standard for UHF RFID [1] FSA is used for scheduling the transmission of tags. In [10] it is already shown that the reader is capable of recovering from collisions with $R \leq M$ tags, where R denotes the number of tags transmitting in the same slot and M is the collision recovery factor. In this case one of these R tags is chosen and acknowledged ($J = 1$) while the responses from other tags are discarded. With this method a 2.6 fold throughput increase is achieved for receivers with $N_{\mathrm{RA}} = 4$ antennas which are capable of recovering from up to eight tags colliding in one slot.

It is feasible to further increase the throughput by acknowledging more than one tag. Given the number N of the tag population and the frame size F, the throughput for a collision recovery factor M under the assumption that we can acknowledge up to J tags per slot is computed [9]:

$$T = \sum_{R=1}^{J} \binom{N}{R} \left(\frac{1}{F}\right)^R \left(1 - \frac{1}{F}\right)^{N-R} R + \sum_{R=J+1}^{M} \binom{N}{R} \left(\frac{1}{F}\right)^R \left(1 - \frac{1}{F}\right)^{N-R} J. \quad (5)$$

The first sum in Equation (5) represents the throughput increase due to the fact that we can ensure collision recovering from R tags while acknowledging up to J tags. The second part considers the throughput increase due to collision recovery of $J < R \leq M$ tags. The second sum goes up to M, thus the slots with a higher number of tags colliding, $R > M$, are not resolvable and do not contribute to the throughput. Based on [9], we have optimized the ratio F/N of frame size and tag population for such scenarios.

Fig. 2 shows the theoretically expected throughput curves of receivers with a collision recovery factor $M = \{2, 4, 8\}$ and two tags ($J = 2$) acknowledged in one slot, together with the curve with a collision recovery factor of $M = 1$, representing conventional receivers that can deal with only one transmitting tag per slot. The calculations are performed for a tag population of $N = 1\,000$.

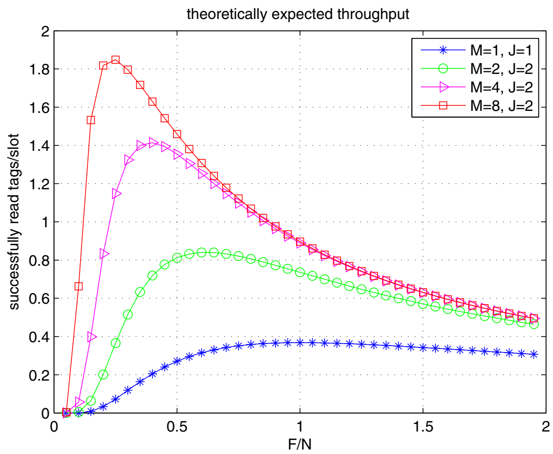

Fig. 2. Expected throughput for $J \leq 2$ with respect to the ratio F/N.

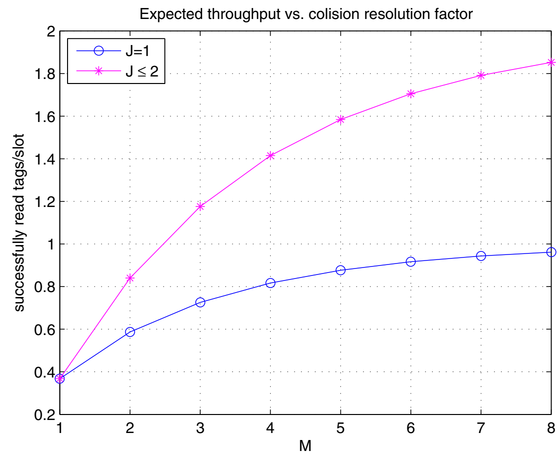

Fig. 3. Expected throughput vs. collision recovery factor M with the optimal ratio F_{opt}/N.

Table I shows the optimal values of the frame size, and the corresponding maximum theoretical throughput as well as the relative improvement with respect to a conventional system with $M = 1$. The optimal frame size values are normalized to the tag population size and are presented for the reader with a collision recovery factor $M = \{2, 4, 8\}$ and two tags ($J = 2$) acknowledged in a slot.

TABLE I
OPTIMAL RATIO F_{opt}/N AND MAXIMAL THEORETICAL THROUGHPUT FOR READERS RESOLVING $M = \{1, 2, 4, 8\}$ COLLISIONS AND $J \leq 2$

System	F_{opt}/N	Exp. Throughput	Rel. Improvement
$M = 1 \quad J = 1$	1	0.368	1.000
$M = 2 \quad J = 2$	0.618	0.841	2.285
$M = 4 \quad J = 2$	0.391	1.415	3.845
$M = 8 \quad J = 2$	0.235	1.852	5.033

Fig. 3 shows the dependence of the expected throughput on the collision recovery factor M and the number of acknowledged tags J in one slot. For both, ($J = 1$) and ($J = 2$), the throughput significantly increases with the collision recovery factor M. For receivers capable of recovering from up to eight tags colliding in one slot (i.e., $N_{\text{RA}} = 4$), the receiver which can acknowledge one tag shows a throughput increase of 2.614 times while the receiver that can acknowledge two tags in one slot offers even a 5.033 times higher throughput, compared to the throughput of a conventional receiver.

IV. CHANNEL ESTIMATION

In the EPCglobal standard for UHF RFID [1] a tag response to the *Query* command consists of a preamble followed by a 16 bit-random number or pseudo-random number. Since the preamble is identical for all tags involved in a collision, we cannot use it for the channel estimation. The bits that follow cannot be used as well, because they are not known in advance and they are different in each conversation round. Hence, we propose an extension of the tag signal by including a ”postpreamble” as shown in Fig. 4. In order to fulfill the channel estimation requirements, our ”postpreamble” is designed to be different for each tag, and mutually orthogonal. Tags encode the backscattered data as either FM0 baseband or Miller modulated of a subcarrier at the data rate [1]. The challenge was to offer optimal channel estimation at minimum ”postpreamble” length.

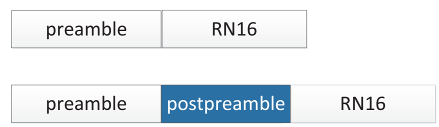

Fig. 4. Tag response according to the standard and the modified tag response.

A. Design of the ”postpreamble”

The length of the ”postpreamble” is strongly influenced by the number of the tags we want to separate in our system. The FM0 coding doubles the amount of bits after the encoding process and do not allow the use of well known orthogonal sequences (i.e., Hadamard). Therefore, one can expect to find only a limited amount of mutually orthogonal sequences, that are equal to the half of the length of the encoded sequence at best. For example for the code length of 12 bits, there are only four mutually orthogonal sequences. Using a full search algorithm [12], we managed to obtain also a set of eight mutually orthogonal sequences of length 16. The maximum number of tags that we are trying to separate in our simulations is eight ($\text{R}_{\text{max}} = 8$) and thus we are using a set of eight mutually orthogonal sequences.

Search-algorithm: Due to the extremely high number of possible vector sets, it is necessary to optimize the search algorithm for mutually orthogonal sequences. The algorithm iterates over increasing set sizes and in each iterations it searches for all unique sets of mutually orthogonal sequences of the size of the particular iteration. A set $\mathbf{S}_i$ of sequences $\mathbf{p}_k$ with exactly i different sequences is called a set of mutually orthogonal sequences if it fulfills the following property:

$$\mathbf{p}_k^{\mathrm{T}}\mathbf{p}_l = \begin{cases} 1, & k=l \\ 0, & else, \end{cases} \tag{6}$$
$$\forall \mathbf{p}_k, \mathbf{p}_l \in \mathbf{S}_i.$$

We developed an iterative algorithm to find the largest set of mutually orthogonal sequences. In each iteration it searches for all unique sets $\mathbf{S}_i$ of mutually orthogonal sequences, which we denote by $\mathcal{W}_i$. In the i^{th} iteration the algorithm searches for the set of all sets of unique mutually orthogonal sequences $\mathcal{W}_i$ of size i based on the set $\mathcal{W}_{i-1}$ obtained in the previous iteration. In the first step our algorithm searches for all unique possible sets of mutually orthogonal sequences of size one: $\mathcal{W}_1$. The trivial solutions in the first iteration are all possible sequences. In the second iteration, all possible pairs of mutually orthogonal sequences are found: $\mathcal{W}_2$. In the following iterations, based on the set of mutually orthogonal pairs of sequences $\mathcal{W}_2$, algorithm searches for all unique sets of three mutually orthogonal sequences, resulting in $\mathcal{W}_3$. The algorithm continues until it can still find at least one unique set of mutually orthogonal sequences of a bigger size.

The set of sequences S_8 that we are using in our simulations, is shown in Table II.

TABLE II
SET OF EIGHT ORTHOGONAL SEQUENCES

Sequence	
$\mathbf{p}_1$	1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
$\mathbf{p}_{18}$	1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1
$\mathbf{p}_{69}$	1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1
$\mathbf{p}_{86}$	1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1
$\mathbf{p}_{171}$	1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1
$\mathbf{p}_{188}$	1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1
$\mathbf{p}_{239}$	1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1
$\mathbf{p}_{256}$	1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1

B. Least Squares estimator - LS

The LS estimator estimates the channel coefficients by minimizing the squared discrepancies between the received signal, on the one hand, and the "postpreamble" on the other hand using [13]:

$$\hat{\mathbf{H}}_{\mathrm{LS}} = \arg\min_{\mathbf{H}} \|\mathbf{r} - \mathbf{S}_{\mathrm{R}_{\max}}\mathbf{H}\|^2 . \tag{7}$$

The LS channel estimator for the "postpreamble" is given by

$$\hat{\mathbf{H}}_{\mathrm{LS}} = (\mathbf{S}_{\mathrm{R}_{\max}}^H \mathbf{S}_{\mathrm{R}_{\max}})^{-1}\mathbf{S}_{\mathrm{R}_{\max}}^H \cdot \mathbf{r}, \tag{8}$$

where $\mathbf{S}_{\mathrm{R}_{\max}} = \{\mathbf{p}_{\mathrm{R}_1}, ...\mathbf{p}_{\mathrm{R}_i}, ...\mathbf{p}_{\mathrm{R}_{\max}}\}$ denotes the set of the $\mathrm{R}_{\max}$ "postpreambles" and $\mathbf{r}$ is the part of the received signal containing the "postpreamble". A perfect knowledge of the "postpreamble" set, as well as a unique distribution of "postpreambles" to the colliding tags, are assumed in our simulations.

V. PERFORMANCE ANALYSIS

The performance of the proposed algorithm is analyzed through MATLAB simulations. The Bit Error Ratio (BER) is computed by Monte Carlo simulations of a varying number of tag responses inside one slot in order to compare the performances. In our simulated system the RFID reader has four receiving antennas. The number R of tags that are in the reader range and are transmitting in this slot, changes from one to eight. We assumed a Rayleigh fading channel. The individual Rayleigh channel coefficients are independent zero mean circularly symmetric complex Gaussian random variables with unit energy. This implies that the two tags participating in the collision experience the same path loss [9]. The simulation is run for different sets of input parameters and it is averaged over $N_{\mathrm{slots}} = 50 \cdot 10^{\frac{\overline{\mathrm{SNR}}[dB]}{10}} + 50$, where $\overline{\mathrm{SNR}} \triangleq \frac{1}{N_{\mathrm{RA}}} \sum_i \frac{E\left\{|h_{i,j}|^2 {a_j}^2\right\}}{N_0}$ is the average signal to noise ratio, and N_0 is the noise power spectral density. For each slot the channel parameters are calculated again.

In Figures 5 - 7 the performance of the MMSE receiver from [10] with perfect channel knowledge is shown while in Figures 8 - 10 the corresponding performance of the MMSE receiver with estimated channels is presented. Around each point in the figures the confidence interval that contains 95% of the obtained results is plotted to evaluate the quality of the simulation.

A comparison of BER values from Fig. 5 and Fig. 8, for the MMSE receiver and two colliding tags, is given in Table III. From this we observe that the MMSE receiver performs almost perfect with the proposed channel estimation method. The BER values are close to those values obtained with perfect channel knowledge.

TABLE III
BER FOR MMSE RECEIVER AND R=2

BER at 30 dB	Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1$	$2.53 \cdot 10^{-2}$	$2.66 \cdot 10^{-2}$
$N_{\mathrm{RA}} = 2$	$0.92 \cdot 10^{-3}$	$1.03 \cdot 10^{-3}$
$N_{\mathrm{RA}} = 3$	$2.17 \cdot 10^{-4}$	$2.86 \cdot 10^{-4}$
$N_{\mathrm{RA}} = 4$	$0.89 \cdot 10^{-4}$	$1.16 \cdot 10^{-4}$

In Table IV a comparison of Fig. 6 and Fig. 9 is given, for the MMSE receiver and four tags transmitting in one slot. Inspecting the BER values we can conclude that for the MMSE receiver with one receiving antenna the BER ratio is too high and the collision cannot be resolved. We need at least two receiving antennas to recover from this collision. In this case our channel estimation method provides very good results.

TABLE IV
BER FOR MMSE RECEIVER AND R=4

BER at 30 dB	Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1$	0.2049	0.2052
$N_{\mathrm{RA}} = 2$	$1.21 \cdot 10^{-2}$	$1.36 \cdot 10^{-2}$
$N_{\mathrm{RA}} = 3$	$5.77 \cdot 10^{-4}$	$7.43 \cdot 10^{-4}$
$N_{\mathrm{RA}} = 4$	$1.61 \cdot 10^{-4}$	$2.15 \cdot 10^{-4}$

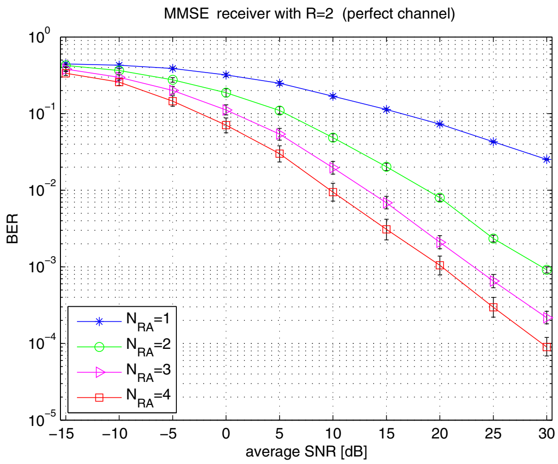

Fig. 5. BER vs. SNR for MMSE receiver with two tags (perfect channel).

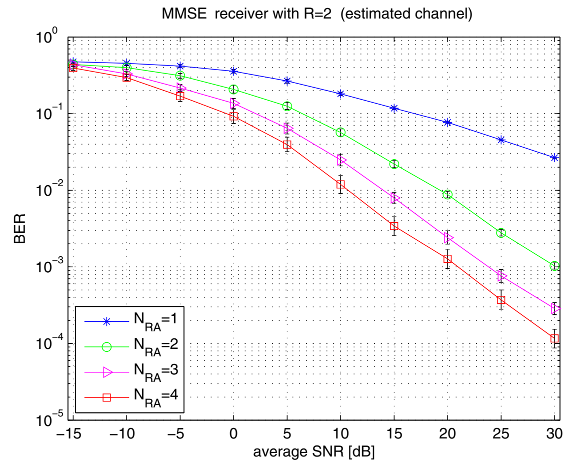

Fig. 8. BER vs. SNR for MMSE receiver with two tags (est. channel).

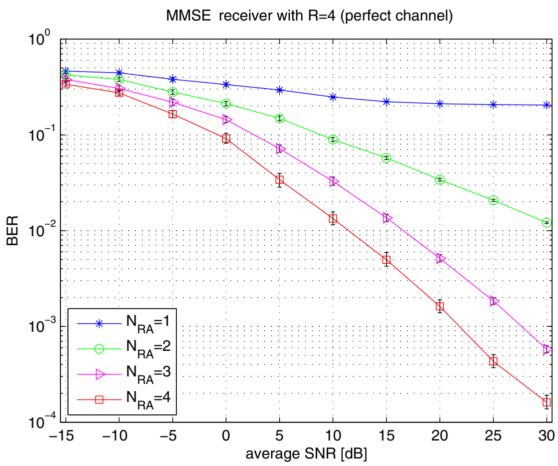

Fig. 6. BER vs. SNR for MMSE receiver with four tags (perfect channel).

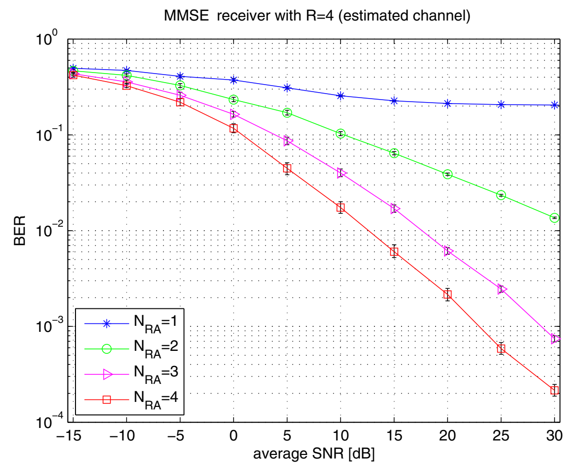

Fig. 9. BER vs. SNR for MMSE receiver with four tags (est. channel).

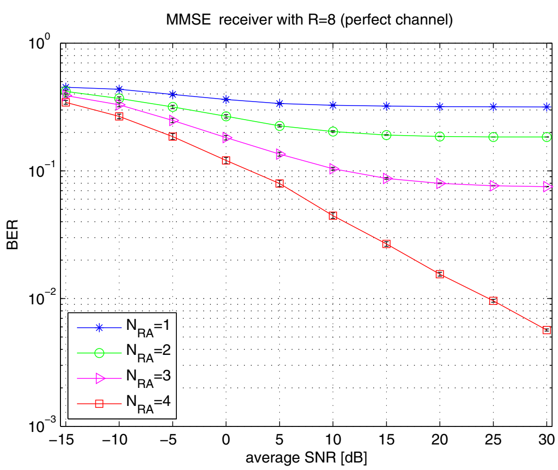

Fig. 7. BER vs. SNR for MMSE receiver with eight tags (perfect channel).

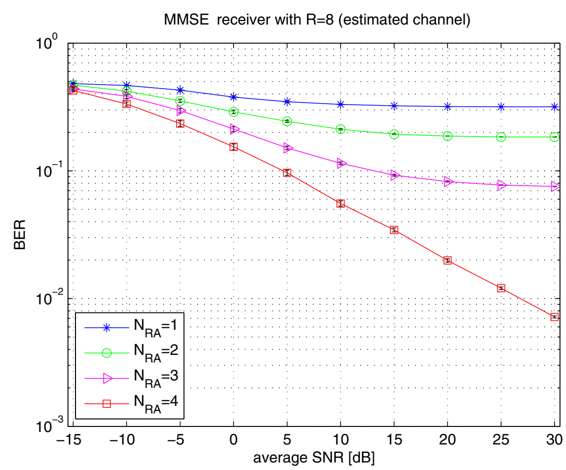

Fig. 10. BER vs. SNR for MMSE receiver with eight tags (est. channel).

A comparison for the MMSE receiver and eight colliding tags, from Fig. 7 and Fig. 10, is listed in Table V. As we have expected for solving the collision of eight tags we need at least four receiving antennas. In case of a smaller number of receiving antennas on the reader side, the resulting BER is too high. The obtained values are similar for both scenarios, the scenario with the perfect channel knowledge and the scenario with the estimated channels. The channel knowledge does not have much impact. Moreover, with four receiving antennas in both scenarios the MMSE receiver can recover from collisions, but as expected with the perfect channel knowledge we obtain a bit better results.

TABLE V
BER FOR MMSE RECEIVER AND R=8

BER at 30 dB	Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1$	0.3170	0.3171
$N_{\mathrm{RA}} = 2$	0.1842	0.1843
$N_{\mathrm{RA}} = 3$	$7.53 \cdot 10^{-2}$	$7.56 \cdot 10^{-2}$
$N_{\mathrm{RA}} = 4$	$5.66 \cdot 10^{-3}$	$7.17 \cdot 10^{-3}$

In Fig. 11 a comparative overview of the expected throughput for MMSE receiver with a different number of receiving antennas at the reader is given, in case of up to eight tags transmitting in the same slot. The maximum of the theoretically expected throughput from [10] is indicated by dashed horizontal lines. The lines correspond to the receivers with a collision recovery factor ($M = 1, J = 1$), ($M = 2, J = 1$), ($M = 4, J = 1$) and ($M = 8, J = 1$), respectively. The receivers with perfect channel knowledge are represented by solid lines and the receivers with estimated channel knowledge by dotted lines. For both scenarios, corresponding groups of curves are approaching their theoretical limits, and it can be observed that with the increase of SNR the curves saturate. Table VI shows the expected throughput values at the SNR of 30 dB.

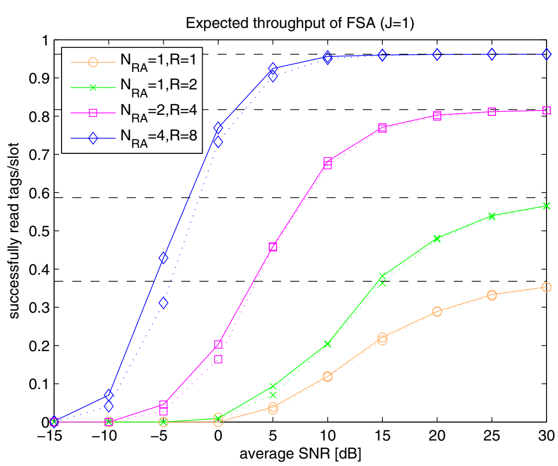

Fig. 11. Expected throughput of FSA scheme for one tag acknowledged (J=1) in a perfect (solid lines) and estimated (dotted lines) channel.

A comparative overview of the expected throughput for the MMSE receivers with the possibility to recover from collisions

TABLE VI
EXPECTED THROUGHPUT OF FSA (J=1)

Throughput at 30 dB	Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1 \quad R = 1$	0.3533	0.3522
$N_{\mathrm{RA}} = 1 \quad R = 2$	0.5658	0.5647
$N_{\mathrm{RA}} = 2 \quad R = 4$	0.8151	0.8151
$N_{\mathrm{RA}} = 4 \quad R = 8$	0.9621	0.9621

and to acknowledge two tags is shown in Fig. 12. The receiver decodes two of the received packets. The packets are from the strongest of all received signals. The chosen received packets are compared with the corresponding transmitted packets. If there is an error in transmission, the number of packets with errors is increased. The same steps are performed in each slot. Finally, the average number of packets with errors (averaged over the slots) is subtracted from the number of acknowledged tags ($J = 2$). In the case when we have singleton slots, just one tag is transmitted per slot; then we are examining just that packet and the average number of packets with errors is subtracted from $J = 1$. The obtained result represents the success ratio of the simulated system $Sr_{i,R}$ with i receiving antennas when R tags are transmitting in the same slot. The expected throughput is calculated as:

$$T_{\mathrm{FSA,i}} = \sum_{R=1}^{M} Pr_R \cdot Sr_{i,R}. \tag{9}$$

Here Pr_R denotes the probability that exactly R tags (out of the total number of tags N), are transmitting in one slot. The MMSE receiver is shown with different numbers of receiving antennas at the reader and with up to eight tags transmitting in the same slot. As in the previous graph the horizontal dashed lines indicate the maximum of the theoretically expected throughput for receivers with collision recovering factor ($M = 2, J = 2$), ($M = 4, J = 2$), ($M = 8, J = 2$), respectively. For comparison also the orange curve that represents a conventional receiver with $M = 1$ and $J = 1$ as well as its theoretical maximum are plotted. Corresponding groups of curves, for the receivers with the perfect channel knowledge (solid lines) as well as with estimated channels (dotted lines), are approaching their theoretical limits. The relative improvement shown in Table I is in accordance with the relation between curves that are representing the proposed receivers and the conventional receiver. From Table VII we observe that with the proposed acknowledgment of two tags per slot we achieve more than five times throughput increase compared with the conventional system in both cases.

TABLE VII
EXPECTED THROUGHPUT OF FSA ($J \leq 2$)

Throughput at 30 dB	Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1 \quad R = 1 \quad J = 1$	0.3533	0.3522
$N_{\mathrm{RA}} = 1 \quad R = 2 \quad J = 2$	0.7481	0.7445
$N_{\mathrm{RA}} = 2 \quad R = 4 \quad J = 2$	1.3830	1.3810
$N_{\mathrm{RA}} = 4 \quad R = 8 \quad J = 2$	1.8370	1.8370

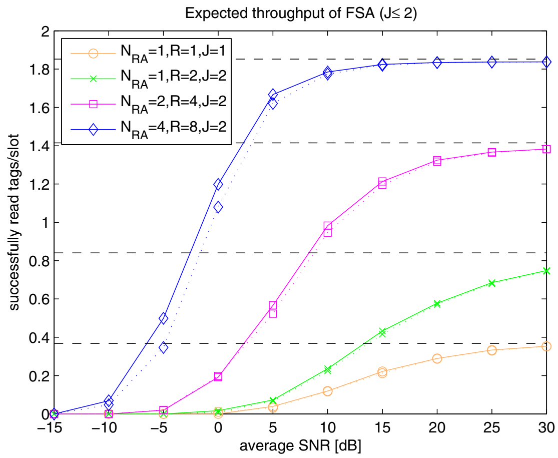

Fig. 12. Expected throughput of FSA scheme for up to two tags acknowledged ($J \leq 2$) in a perfect (solid lines) and estimated (dotted lines) channel.

VI. Conclusion

In this paper, we identify the increase of the theoretical throughput of an FSA RFID system with multiple antennas for physical layer collision recovery. For a reader capable of successfully reading and acknowledging two tags per slot with up to eight tags colliding, a throughput increase of approximately 5.03 times the throughput of a conventional RFID reader is achieved. Furthermore, we propose a method for channel estimation in collision scenarios. In our proposed method the tag signal is modified by adding a "postpreamble". The influence of the estimated channel on the performance is investigated by simulations. The obtained results show that our proposed method provides excellent results in comparison to perfect channel knowledge. There is not a significant decrease of the performance and still it is possible to recover from a collision as long as the number of tags is not larger than two times the number of receiving antennas at the reader. Our next important step is to investigate the adaptation of the protocol in order to acknowledge two tags in a single slot. Moreover, we are going to analyze the influence of randomly selected tags with non orthogonal "postpreamles" on throughput.

Acknowledgment

This work has been funded by the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility, and its industrial partner Infineon Technologies. The financial support by the Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development is gratefully acknowledged. We finally like to thank Christoph Mecklenbräuker for his fruitful discussions and stimulative thoughts.

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